

# New Concepts for Improving Dynamic Range in (M)PDV Systems

E. Kirk Miller

National Security Technologies, LLC  
Special Technologies Laboratory

With advice, support and input from (among many others!):

NSTec:

Brandon LaLone, Tom Waltman, Jerry Stevens, Ed Daykin, Mike Peña, Chan Jung, Kevin Lee, Eric Larson, Abel Diaz, Marylesa Howard, Bob Berglin, Mike Grover, Ben Valencia, Dale Turley, Rachel Posner, Dan Frayer, Araceli Rutkowski, Bruce Marshall

LANL:

David Holtkamp, Matt Briggs, Patrick Young, Mike Furlanetto, Mike Ulibarri, Benjie Stone, Lenny Tabaka

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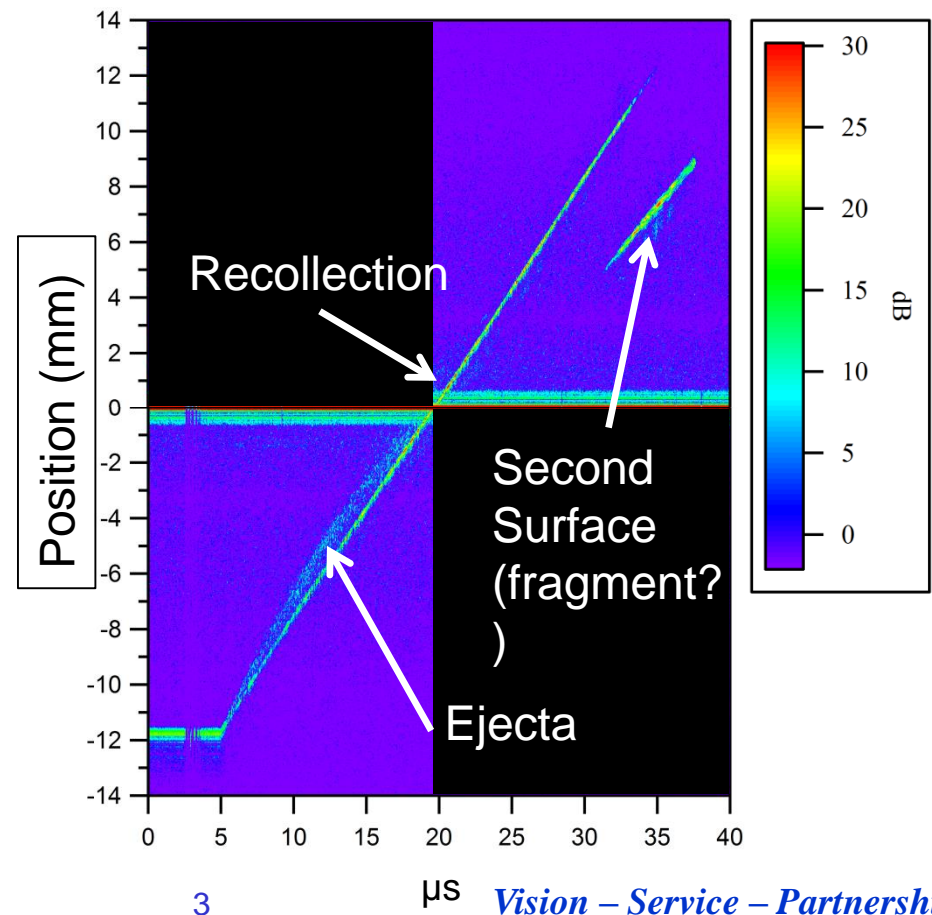
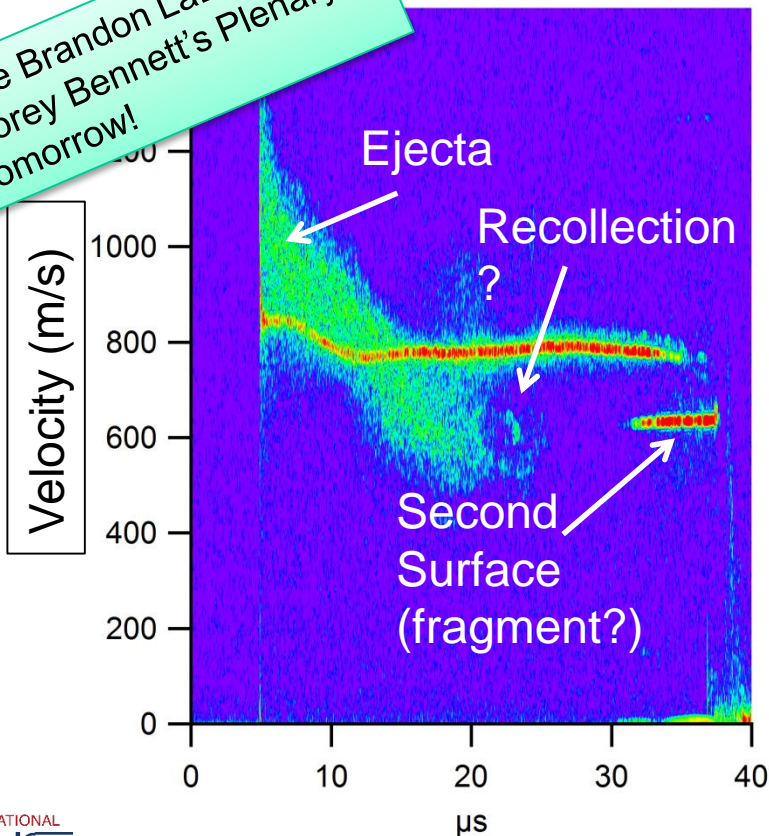
# Overview

- Where are we now
  - Small signal return: Nearly shot-noise limited
  - Large signal return: effective-bits limitation
  - Role of EDFA's
- Deep-time Multiplexed PDV
- Modulated launch-light
- Dynamically refocusing probe optics
  - Resonantly-driven GRIN lens
  - Optically-actuated lens
- Conclusions and next-steps

## Why “Dynamic Range?”

- Some experiments have low and/or widely-varying signal returns
- Some experiments have “clouds” of material obscuring the surface
- Limited launch power and probe efficiency

See Brandon LaLone and  
Corey Bennett's Plenary  
tomorrow!



## Some back-end schemes have been tried

- Modulate the LO to increase RF amplitude
- Optical auto-gain control on signal return, using SOA
- RF gain control on back-end
- ... none of these provide convincing performance improvements when peak light-returns are  $< -20$  dBm

## Low signal returns & the shot-noise limit

- At shot-noise limited signal-to-noise of 1:1:
  - B is bandwidth (Hz),  $\eta$  is quantum efficiency

$$SNR \equiv \frac{\langle i_s^2 \rangle}{\langle i_n^2 \rangle} = 1 = \frac{\eta P_s}{h\nu * B}$$

- For 1550 nm light, we get:

$$P_{shot-noise-limit} = 10 \log \left( \frac{B}{1 \text{ MHz}} * \frac{1}{\eta} \right) - 99 \text{ dBm}$$

- For  $\eta=0.7$  (0.9 A/W), the shot-noise limit is -81 dBm in a 50 MHz BW
  - e.g. 2000-point FFT on a 50 GS/s record
- A modern, 6-bit (effective) scope will have ~ 68 dB from its noise floor to full-scale
- So, you should be able to see from the shot-noise limit up to -13 dBm!

# EDFA effect on Small Signals

- Noise from LO-ASE:

$$\langle i_{ASE}^2 \rangle = 2\eta^2 e^2 \frac{P_{LO}(P_{ASE}/Hz)}{(h\nu)^2} * 0.5 * B$$

- Add that to the LO Shot-noise to get total noise:

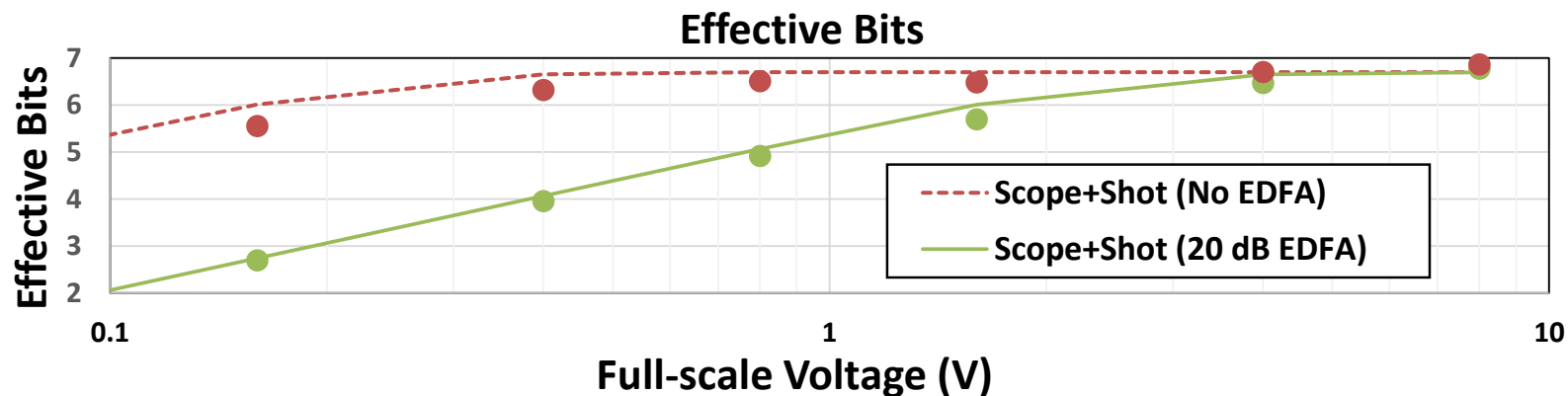
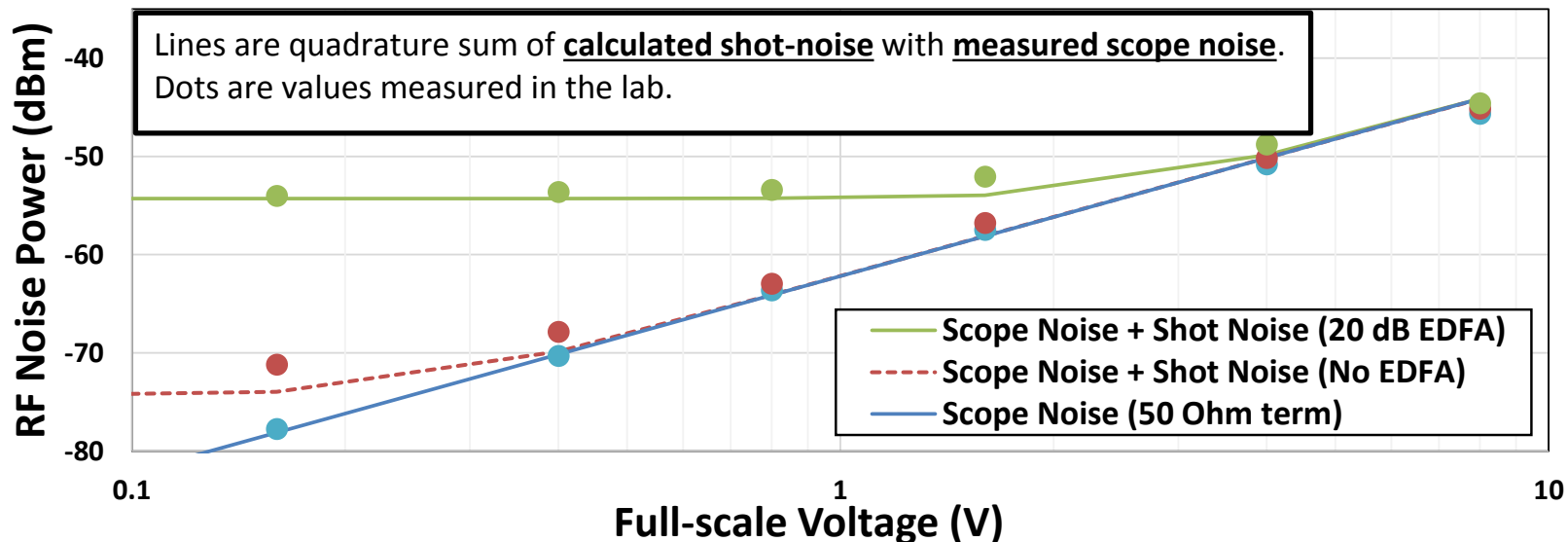
$$\langle i_{n\_TOTAL}^2 \rangle = \langle i_{LO\_SHOT}^2 \rangle \left( 1 + \frac{\eta * (P_{ASE}/Hz)}{2 * h\nu} \right)$$

High-gain, fully  
inverted EDFA

$$\langle i_{n\_TOTAL}^2 \rangle \approx \langle i_{LO\_SHOT}^2 \rangle * \eta_{PD} * G_{EDFA}$$

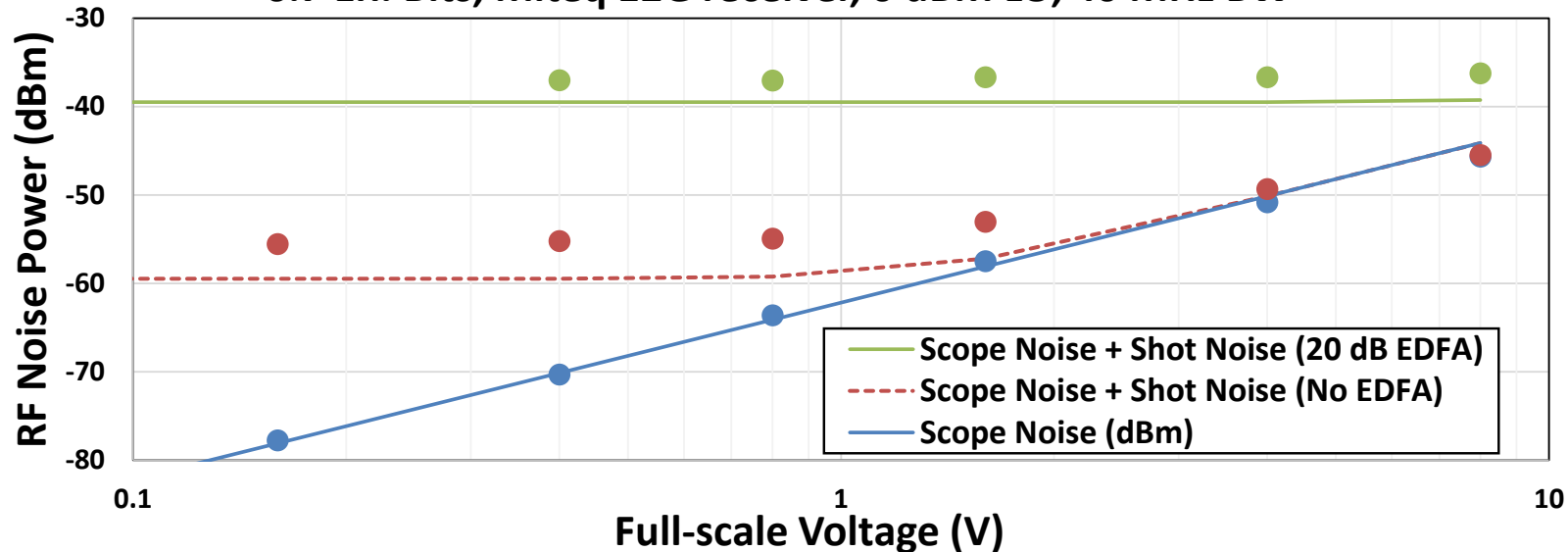
# Lab Data: Discovery 402 Receiver

## Shot-noise Limited (Electrical) Noise Power 6.7 Eff. Bits, DSC402 receiver, 0 dBm LO, 40MHz BW

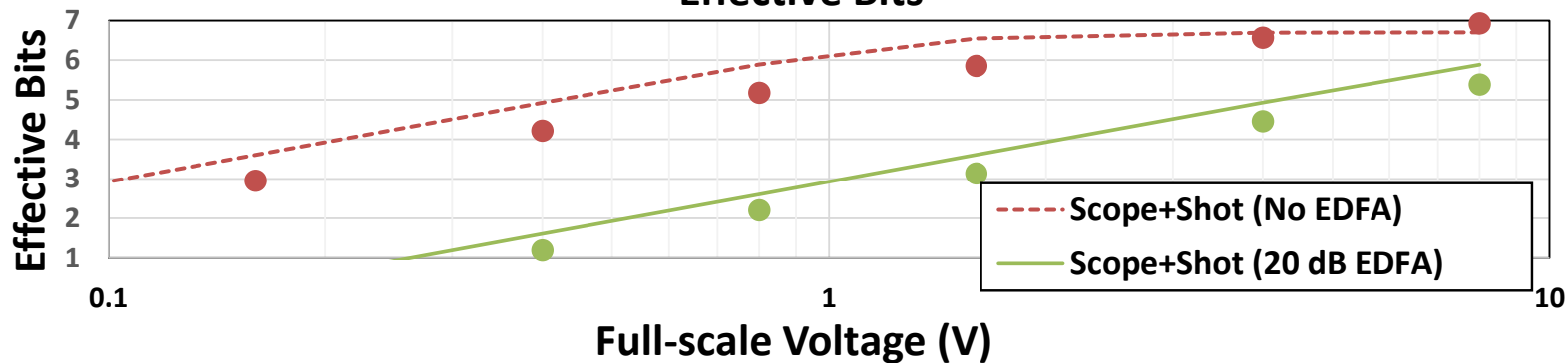


# Lab Data: Miteq 12G Receiver

Shot-noise Limited (Electrical) Noise Power  
6.7 Eff. Bits, Miteq 12G receiver, 0 dBm LO, 40 MHz BW



Effective Bits





## Top-end of the range: Heterodyne Signal Amplitude

PD current, from the textbook:  $\langle i_s^2 \rangle = 2 \left( \frac{e\eta}{h\nu} \right)^2 P_{LO} P_S$

Power into 50 Ohms:

$$P(mW) = \frac{Transimpedance^2 * \eta^2}{16000 \Omega * V^2} * GAIN_{OPT+RF} * P_{LO}(mW) * P_S(mW)$$

$$P_{RF}(dBm) = P_{LO}(dBm) + P_S(dBm) + 10 \log_{10} \left( \frac{Transimpedance^2 * \eta^2}{16000 V^2 \Omega} * GAIN_{OPT+RF} \right)$$

Power gain of O-E conversion  
(~23 dBm for MITEQ 12 GHz receiver)

So, if you have your scope set to 2 V full-scale (+10 dBm), and you are using the Miteq 12G receiver (23 dBm OE gain) with 0 dBm LO, you would expect to fill your scope with -13 dBm of signal light on the receiver.

## Back-end configurations that get us NEAR Shot-Noise limit

- InGaAs photodiodes at 1550 nm:
  - 75% quantum efficiency, or 0.9 A/W
- Commercial receivers (Miteq, Discovery, NewFocus) with nominal LO power of 0.5 – 2 mW
  - This gets us to regime where **LO shot-noise dominates** over other noise sources
  - Higher LO can bring signal (and noise) up into scope's range
- Bare photodiode(s) with low-noise amplifier and LO up to 30 mW
  - No advantage for (MPDV) over amplified receivers
- Add a commercial, low-noise EDFA preamp to any of the above
  - Raises both signal and noise without changing SNR
  - Good way to compensate downstream (e.g. multiplexing) losses
  - Can help bring signals into scope range
- Modern, high-bandwidth digitizers

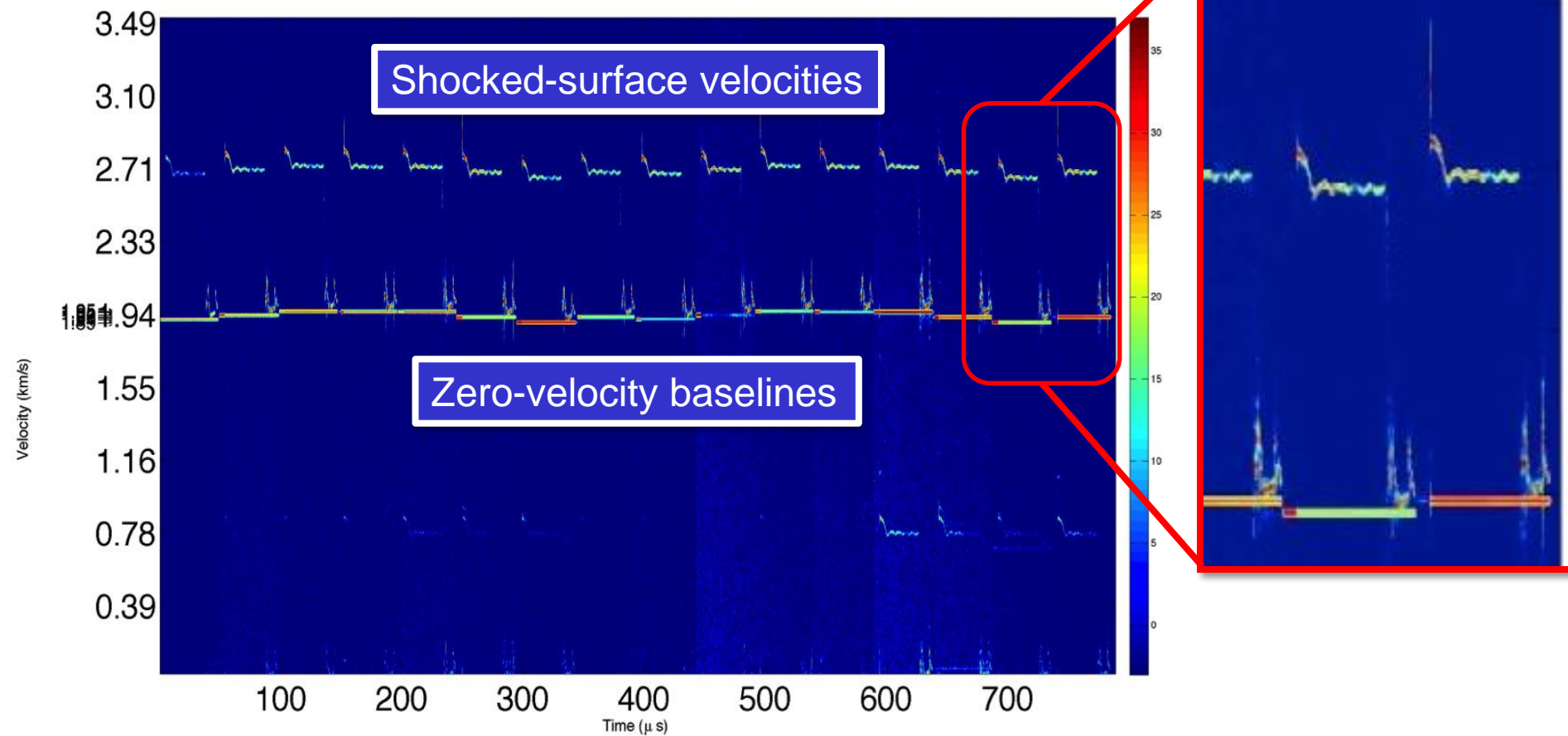
# Deep-time Multiplexing

- Shot-noise-limited reality: LO shot-noise dominates
- Frequency-multiplexed (and early deep-time multiplexed) MPDV's have multiple LO's on receiver simultaneously
- The NOISE comes from all LO's, but each channel's SIGNAL comes only from its own LO
- We needed to switch the LO light with the signal light
  - Noise dropped by 4x (6 dB)
- Added benefits:
  - Easier to field
  - Data is easier to analyze
  - Less recording bandwidth required

# Deep Time MPDV Spectrogram

- Data from deep-time multiplexed experiment
- 16 data channels multiplexed

CH\_3021 @ 2048/128/0

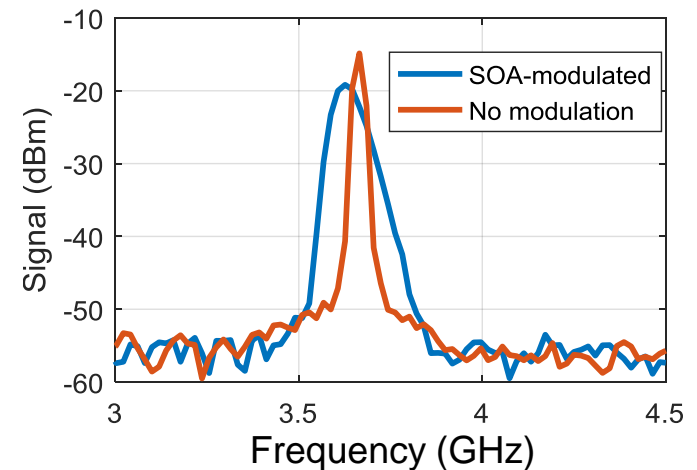


# For weak returns, we just need more signal photons!

- Ground-rules:
  - CW light is limited to ~ 20 mW per channel
  - Total power through probe
  - Total power to surface
- Two approaches:
  - Increase the launch power without “breaking the rules”
  - Improve light collection for cases of ejecta obscuring surface

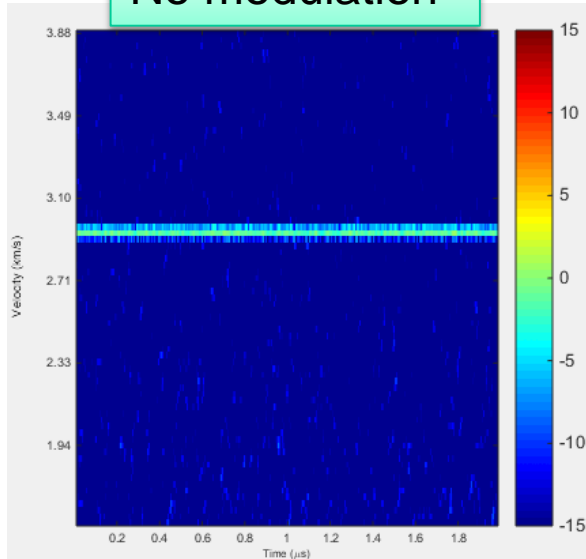
# One solution: Modulated launch light

- AO modulator:
  - BW is good enough (50 MHz)
    - don't need Mach-Zehnder
  - High power handling
  - Polarization-insensitive
  - SOA broadens line when modulated
- FPGA-based control
  - 40 MHz master clock
  - 10 MHz ADC & DAC
  - Digital modulation line (up to 50 MHz square-wave)
  - Dual, programmable trigger inputs
- Modulation schemes
  - Free-running, e.g. 50% and 10% duty cycles
  - Triggered waveform
  - Feedback (~ 500 ns)

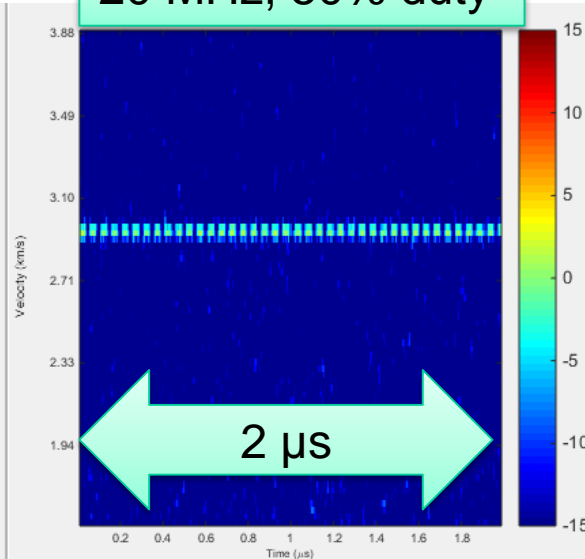


# Free-running modulation, -60 dBm time-average signal

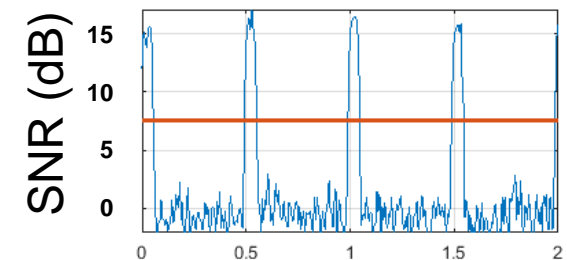
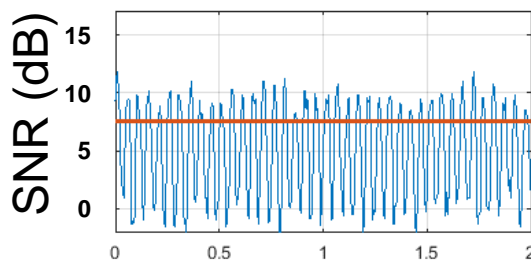
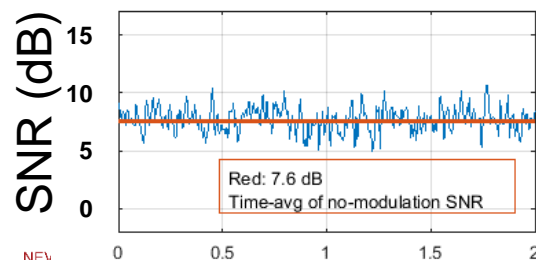
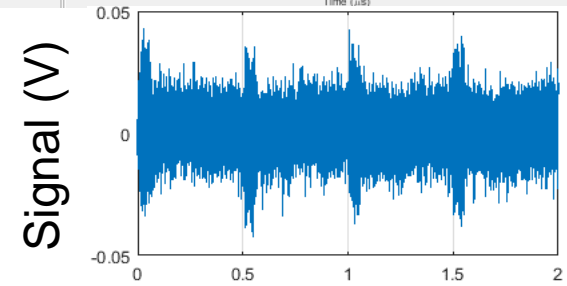
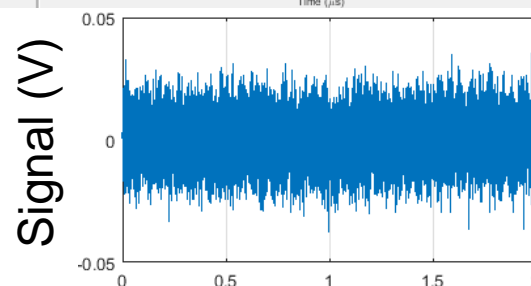
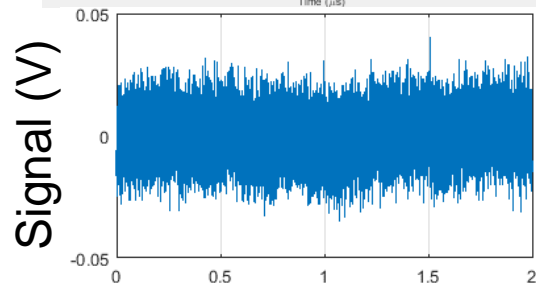
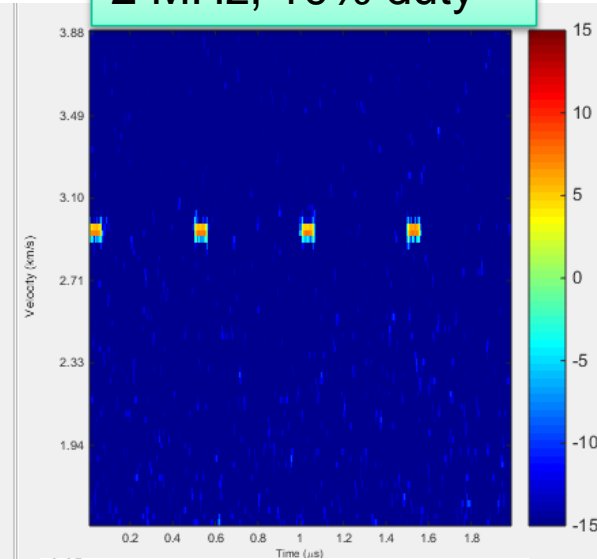
No modulation



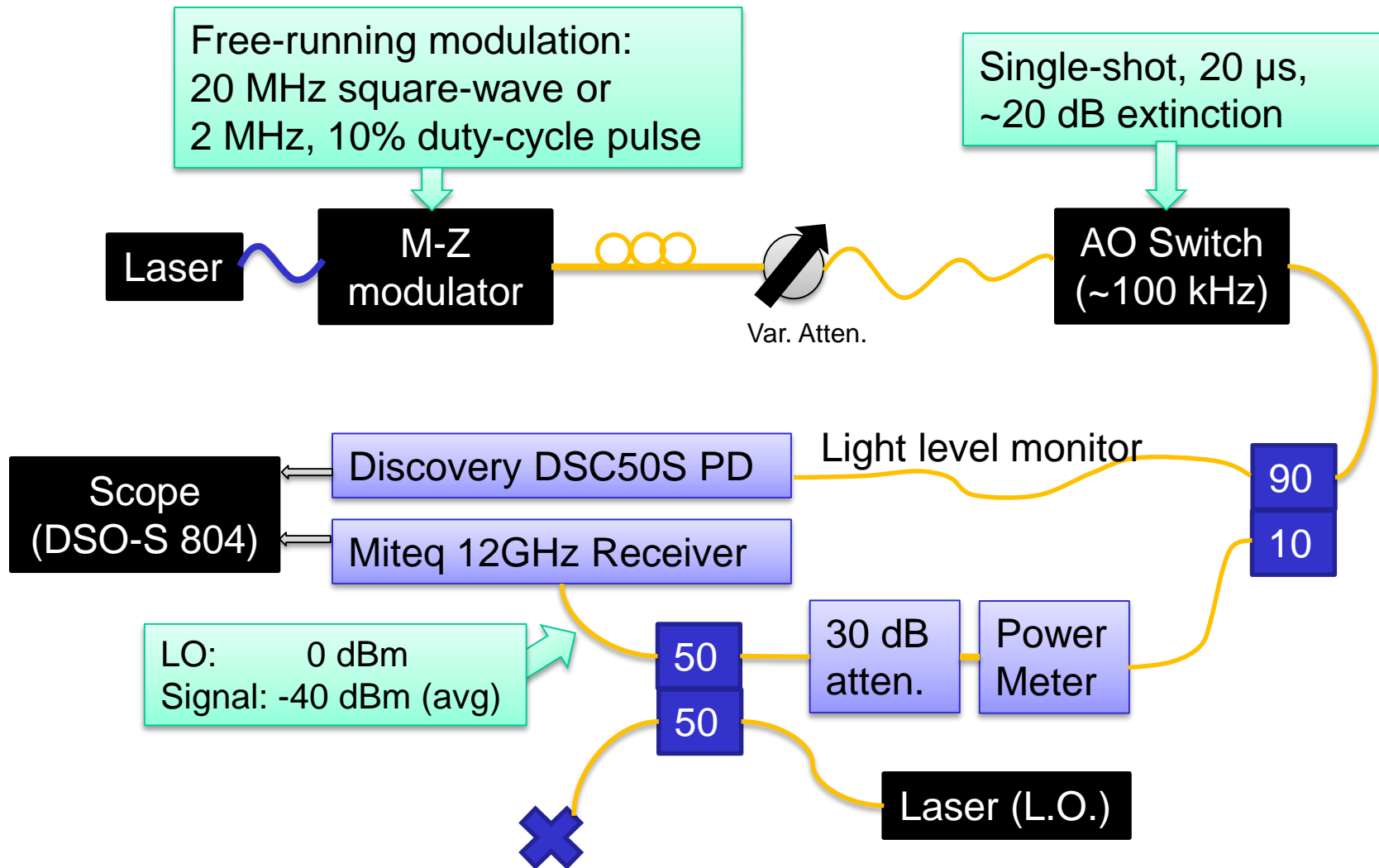
20 MHz, 50% duty



2 MHz, 10% duty

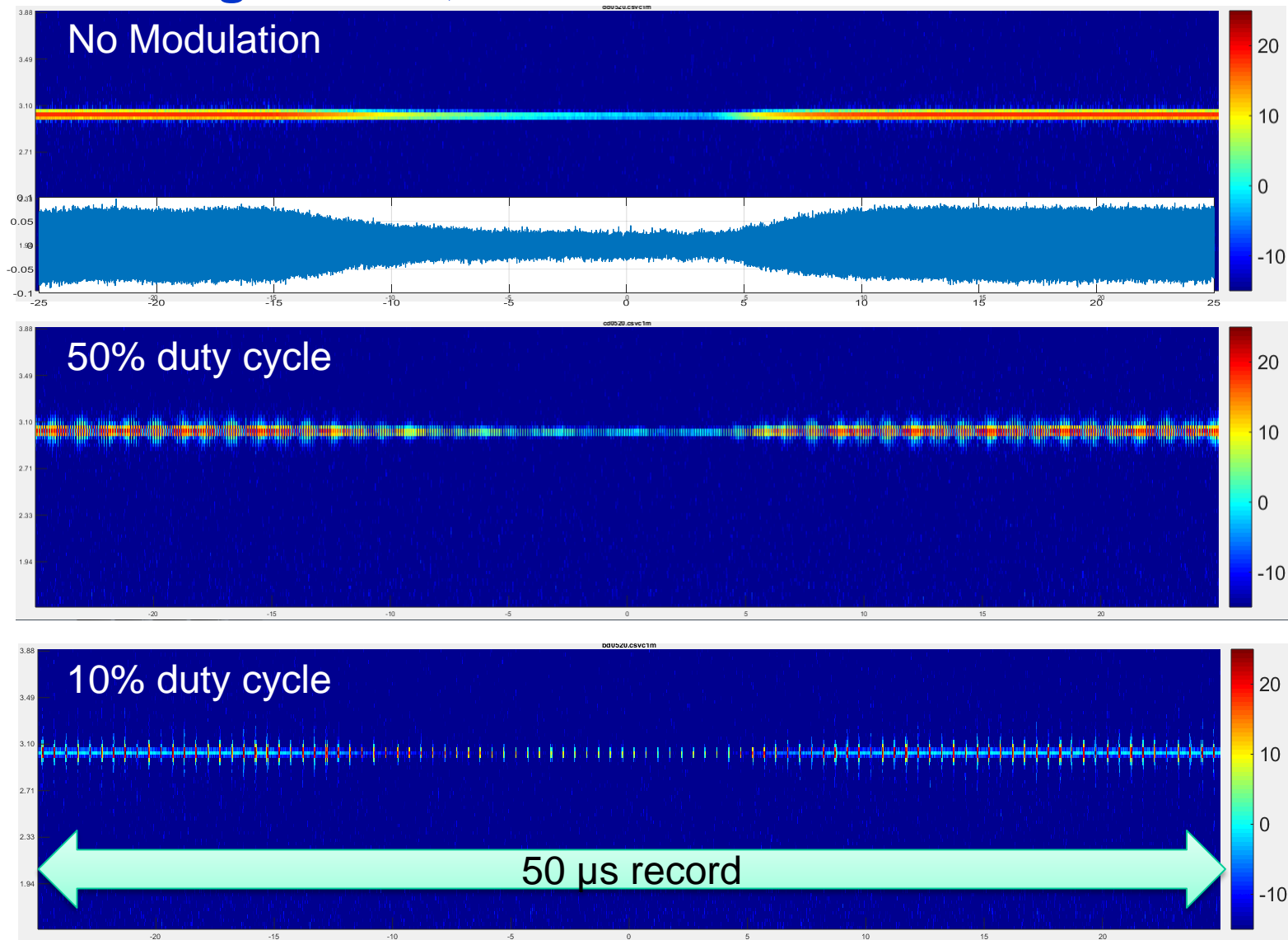


# Lab simulation of dynamic signal loss

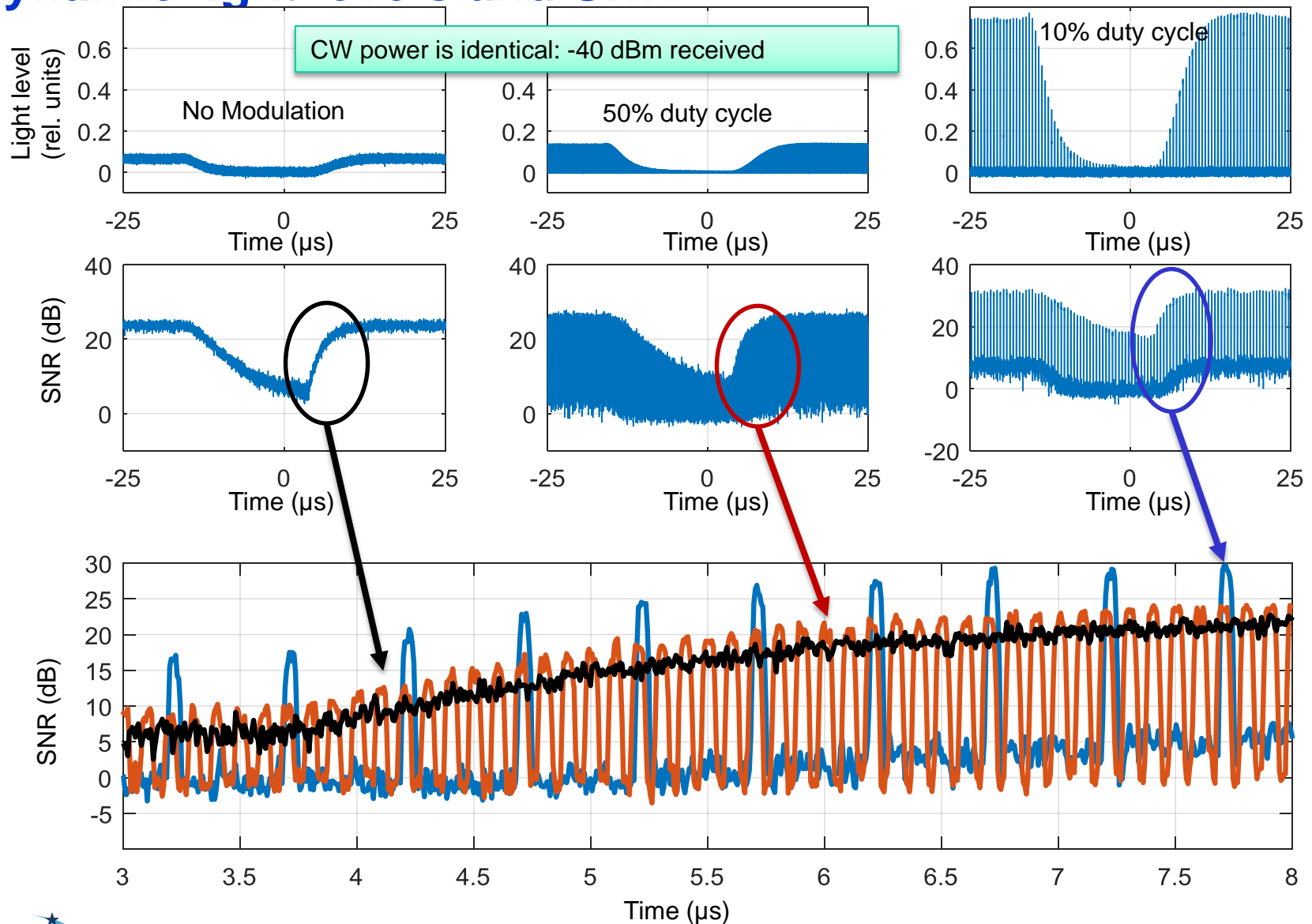




# Dynamic signal loss, -40 dBm to -60 dBm



# Dynamic light levels and SNR



## Launch-modulation: next steps

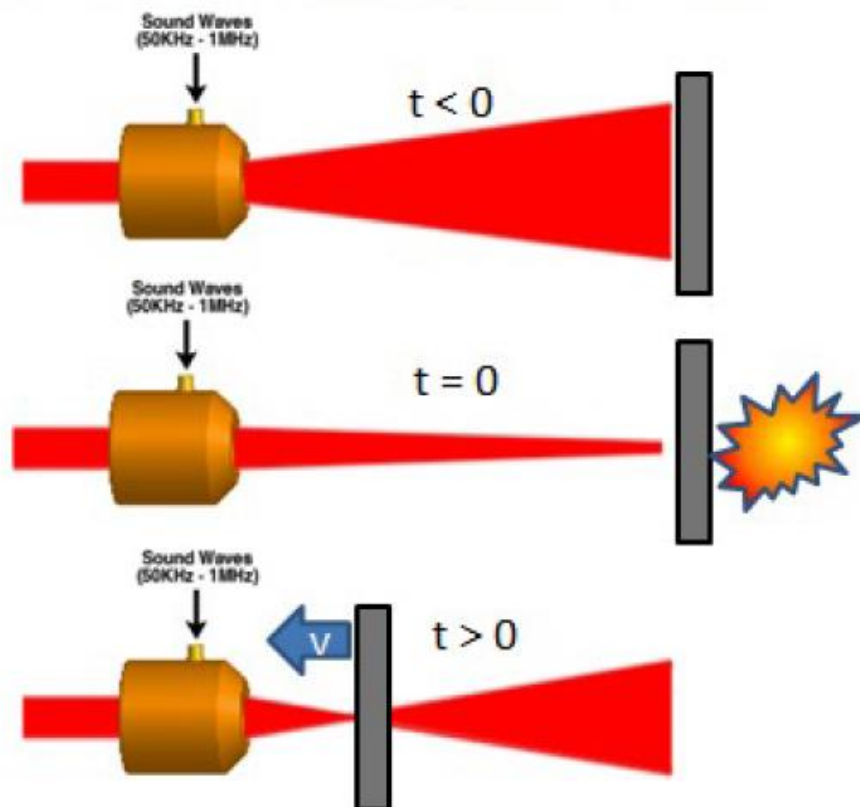
- Build up real-time modulation system:
  - FPGA
  - 50 MHz AO Switch
- Implement modulation schemes:
  - Free-running, variable duty cycle
  - Triggered, programmable output
  - Feedback on return light level ( $< 1 \mu\text{s}$ )
- Field this system on small-scale shots at NSTec / STL
  - Summer 2016

## Electrically-actuated lens: TAG Optics

- Resonantly-driven, cylindrical liquid cell
- Density modulation creates gradation of index:
  - Compression: converging focus
  - Rarefaction: diverging focus
- For IR operation, standard resonant frequencies are 140 – 340 kHz
- Higher resonant frequencies have smaller effective apertures
- Need to figure out relationship between focal length (or effective focal length),  $S2''$ , and collection efficiency

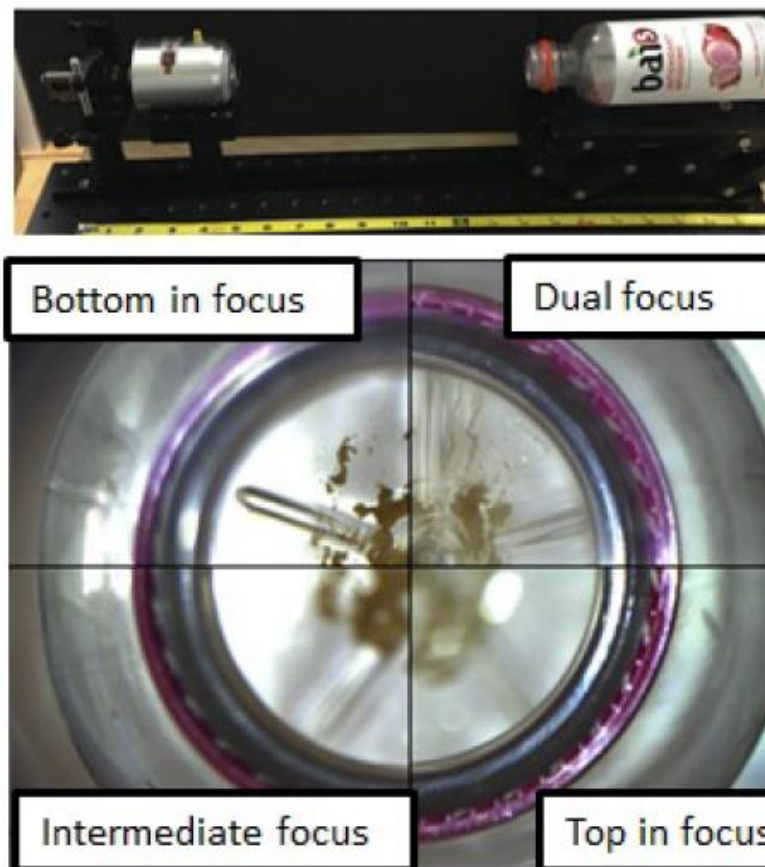
# Original concept: Track the Surface

GRIN Lens refocusing with period of 1 – 20  $\mu\text{s}$



Source: tag-optics.com

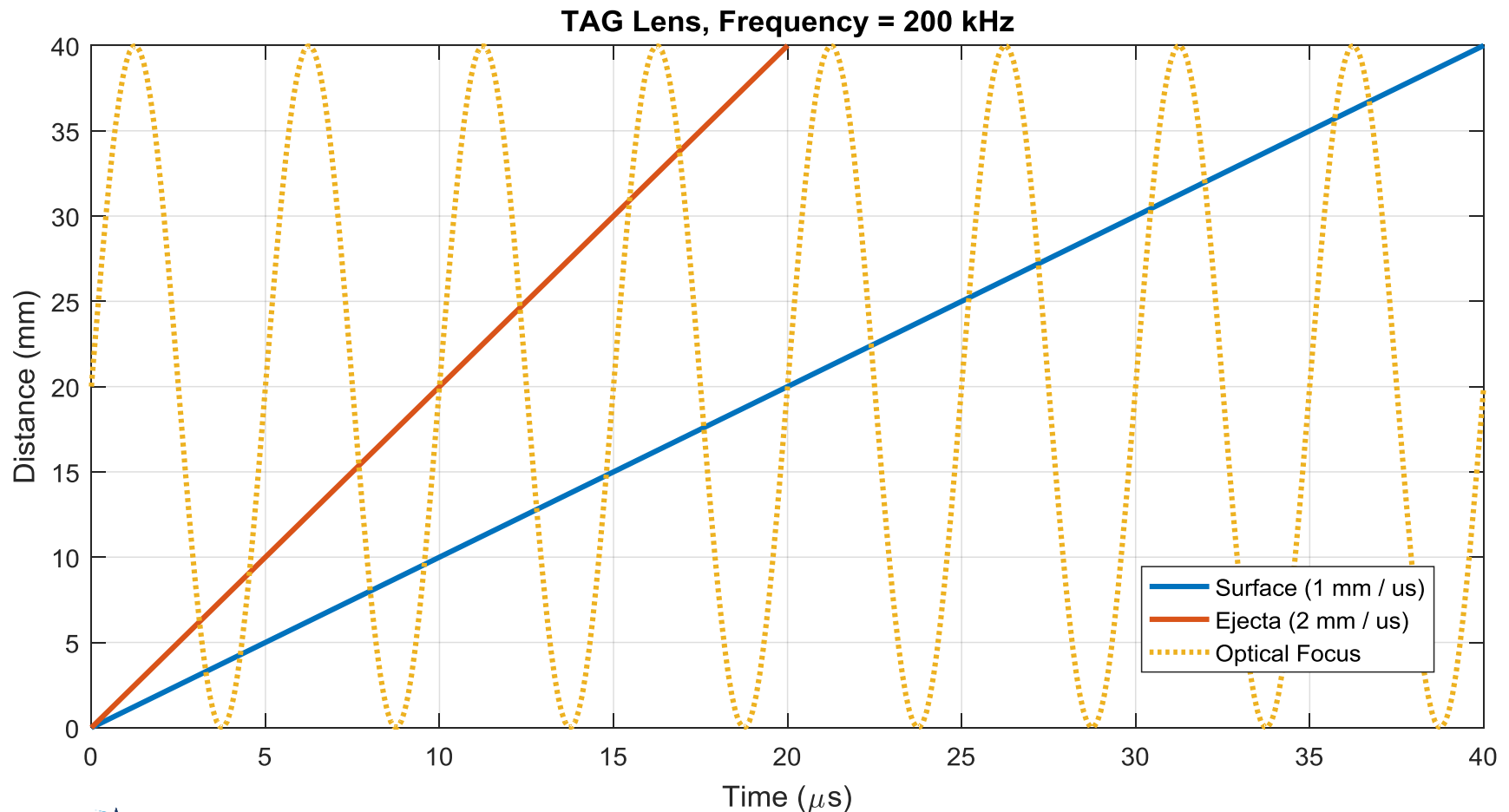
Lab demo with juice bottle



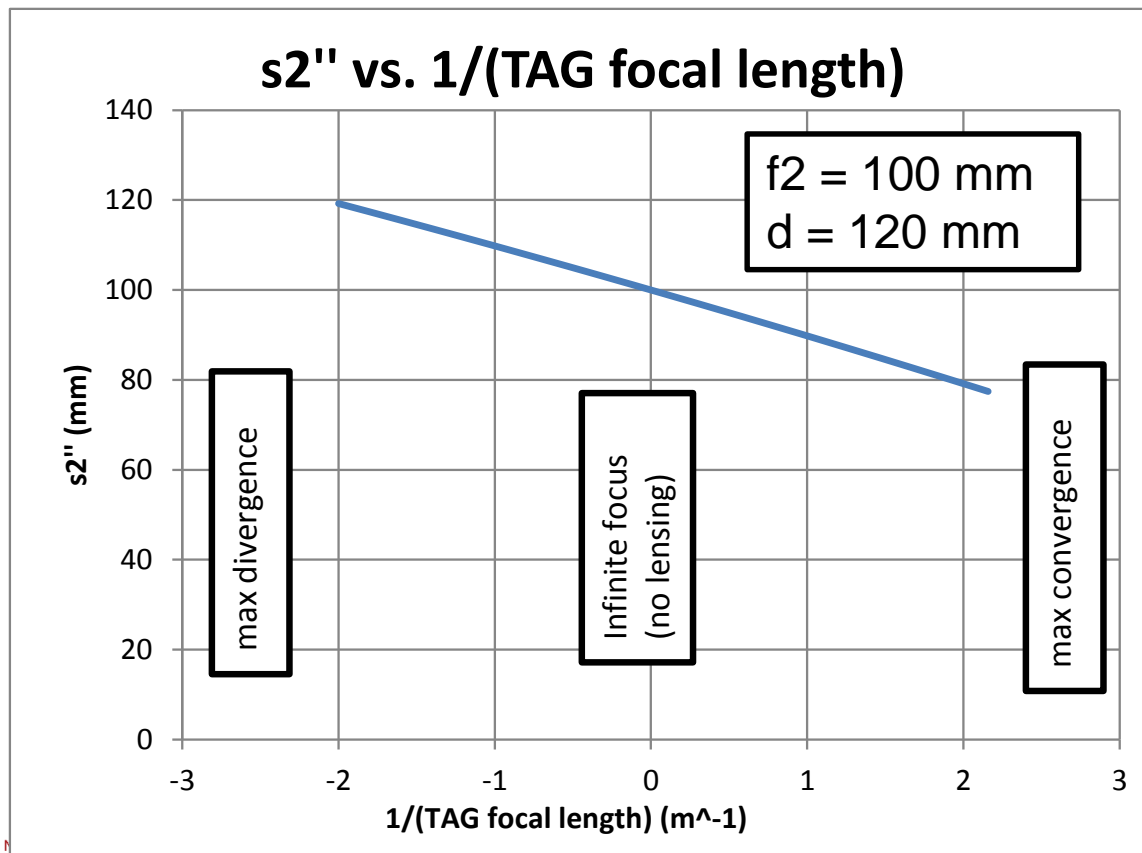
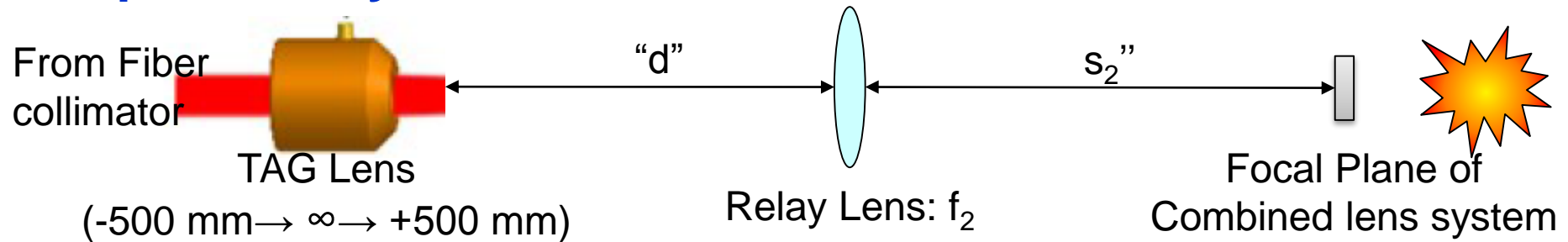
But... resonant frequencies are too high for 10  $\mu\text{s}$  experiments!

## Next Approach: Free-running

Each object passes through focus twice every 5  $\mu\text{s}$



# Optical relay for TAG Lens



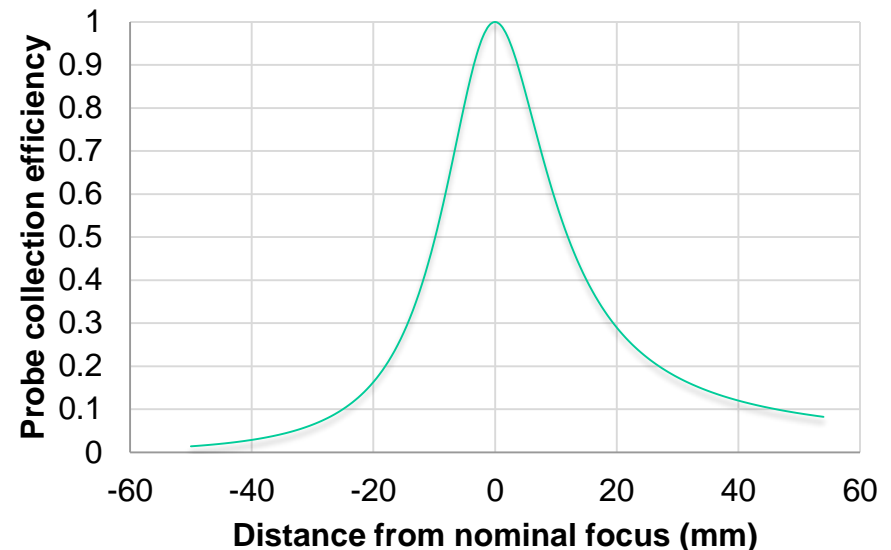
For this configuration:

- Focal point slews between 75 mm and 120 mm from relay lens.
- Demonstration shots will use right-angle pellicle to protect fixed optical system

## Expected optical performance

- Predictions are for 5-10 dB rejection of objects 20 mm from nominal focus
- Should improve tracking of surface behind ejecta

### Predicted collection efficiency

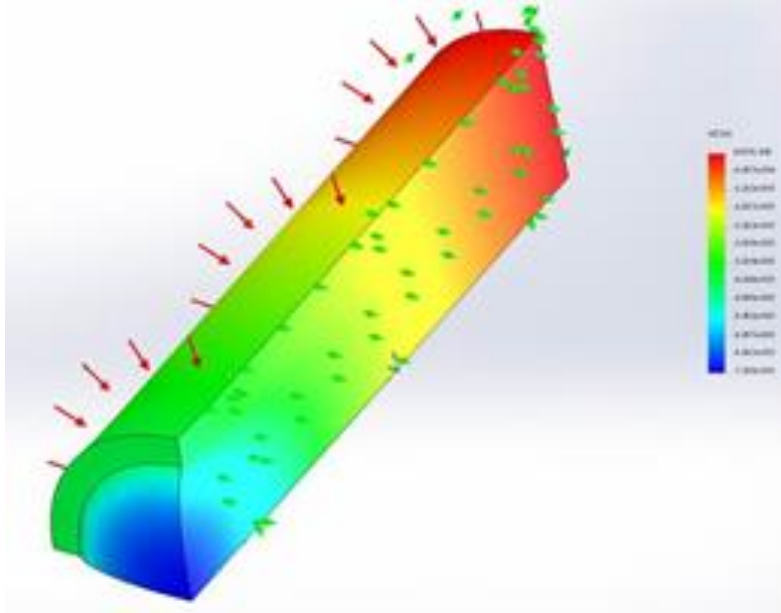




# Optically Actuated Lens

- Objective: actuate dynamic lensing *through the fiber*

100  $\mu\text{m}$  polymer fiber in steel tube

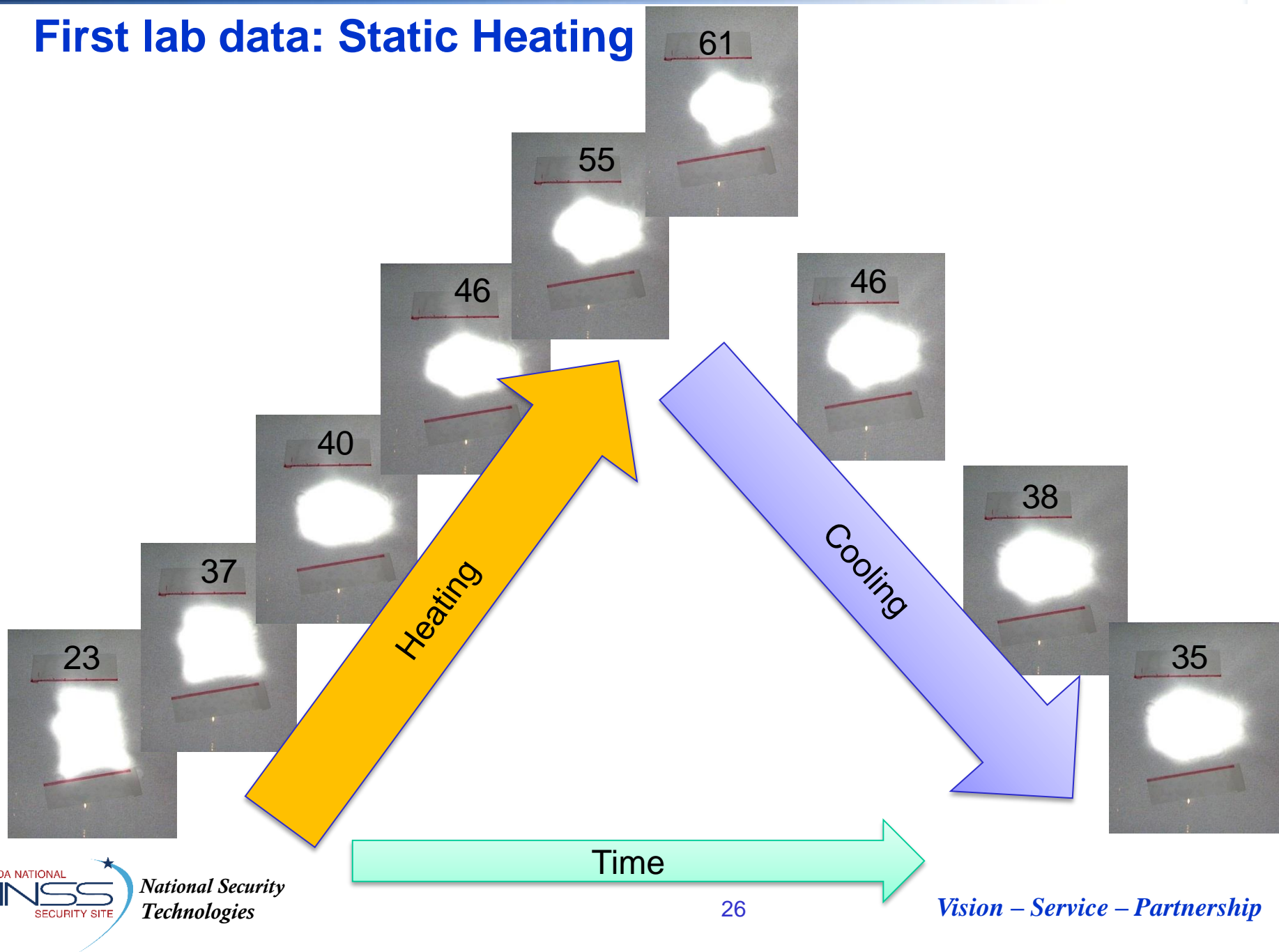


Polymer expansion (+30°C)  
causes deformation and end.  
Focal length ~40 mm

Next steps:

- Test simulation predictions:
  - Measure optical focusing
  - Measure physical deflection
- Custom fiber-draw with doped polymer
- Assemble dynamically actuated probe
- Test on dynamic shots

# First lab data: Static Heating



## Physical feasibility

- Volume  $\sim 1 \text{ mm}^3$
  - Mass  $\sim 1 \text{ }\mu\text{g}$
  - Energy to heat by  $10^\circ \text{ C} \sim 10 \text{ }\mu\text{J}$
  - Power in  $10 \text{ }\mu\text{s} \sim 1 \text{ W}$
- 
- Use current-pulsed, high-power laser diodes
  - Use cladding-pumped fiber to deliver pump + signal

## Dynamic-refocus: Next steps

- TAG lens
  - Assemble optical test bench in lab to quantify dynamic-range improvement during resonant operation
  - Begin designing dynamic experiments
- Optically actuated lens scheme
  - Mechanical modeling of larger polymer fibers
  - Verification of mechanical modeling: optical and physical
  - Begin considering pump and absorber system that could create the lensing desired

## Summary: Places to gain dynamic range

- We are within a few dB of the shot-noise limit with back-end hardware
- Where can we squeeze more dynamic range?
  - Modulate launch power
    - More launch photons → more DR
    - May still run up against backscatter and probe power-handling limitations
  - Dynamically refocusing probe optics could improve collection over a wider range of probe-surface distances
    - Potentially useful in discrete-probe configurations
  - Balanced detection
    - Need better selection of lab-friendly receivers
    - 3 dB more signal (using 50/50 combiner)
    - More efficient use of LO power
    - Rejection of common-mode power swings

## Backup slides

# Shot-noise limit (Optical power)

$$SNR \equiv \frac{\langle i_s^2 \rangle}{\langle i_n^2 \rangle} = 1 = \frac{\eta P_s}{h\nu * B}$$

$$P_{shot-noise-limit} = \frac{B * h\nu}{\eta} = \frac{B * 1.28 \times 10^{-19} J}{\eta} = \frac{B}{1 \text{ MHz}} \frac{1.28 \times 10^{-10} mW}{\eta}$$

$$P_{shot-noise-limit} = 10 \log \left( \frac{B}{1 \text{ MHz}} * \frac{1}{\eta} \right) - 99 \text{ dBm}$$

# SNR relationship to Effective-Number-of-Bits (ENOB)

Normalize for fraction of full-scale used

SNR increase by using frequency-domain analysis

$$SNR_{f,dB} = (6.02 \times ENOB) + 1.76 + 20 \log \left( \frac{2A}{V_{FS}} \right) + 10 \log \left( \frac{N_{FFT}}{2} \right)$$

ENOB = effective bits for digitizer,  $V_{FS}$  = full scale voltage,  $A$  = RMS amplitude of applied signal  
(See Wiley Encyclopedia of Electrical and Electronics Engineering, Vol. 18, J. Blair)

Number of bits as function of  
SNR, fraction of full-scale,  
FFT Points

“Frequency-domain  
Number of Bits”

$$FNOB = \frac{1}{6.02} \left[ SNR_{f,dB} - 1.76 - 20 \log \left( \frac{2A}{V_{FS}} \right) - 10 \log \left( \frac{N_{FFT}}{2} \right) \right]$$

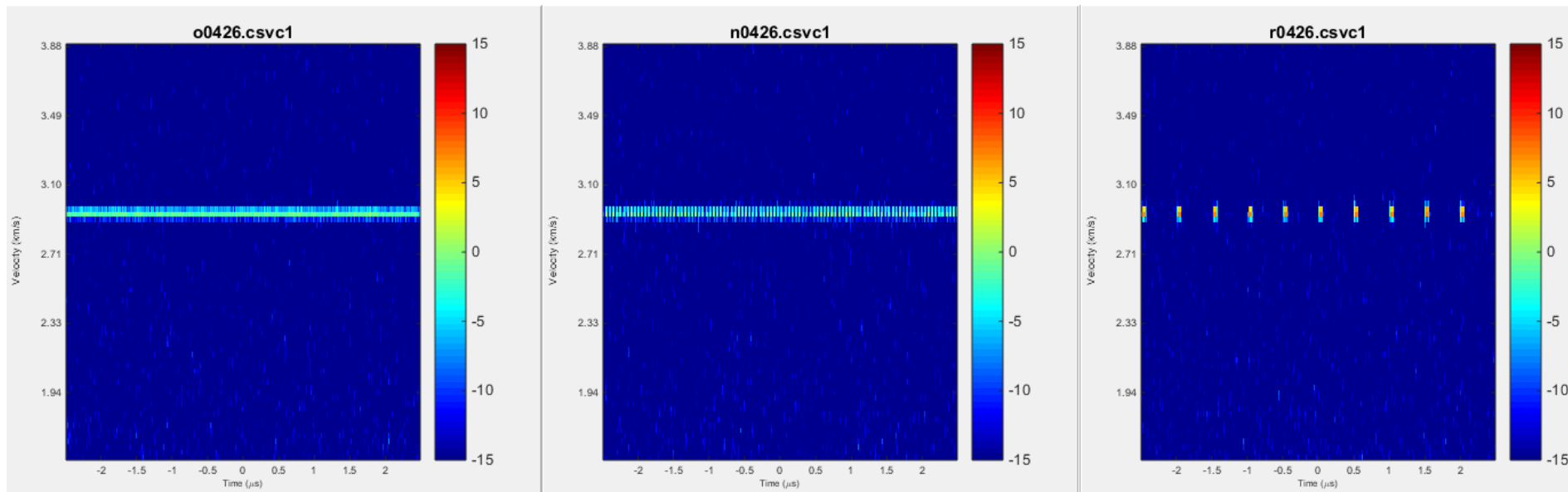
“signal” cancels out...

$$FNOB = \left( \frac{1}{6.02} \right) * \left[ 10 \log \left( \frac{V_{FS}^2}{50\Omega} * 1000 \right) - noise_{dbm} - 7.78 - 10 \log \left( \frac{N_{FFT}}{2} \right) \right]$$

... Just a noise measurement! Measure with receiver on, LO power at nominal.



# Full-time (5 $\mu$ s) spectrograms of free-running modulation



## Advantages to balanced receiver

- For deep-time MPDV, no problems when LO switches
- Don't throw away LO or signal photons
  - 3 dB signal gain for 50/50 combiner
  - Not a problem if you are already using 90/10 combiners
- ASE-ASE is common-mode
  - Not commonly a problem
  - In balanced receiver, suppressed by 20-30 dB